

Design and Analysis of a Band-Notched Staircase Ultra-Wideband Antenna

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Abstract—A compact ultra-wideband planar monopole antenna with a notched band at WLAN frequencies is presented. The antenna is fed using a finite ground coplanar waveguide and has a structure consisting of stair-shaped radiator and ground plane. The notched band is implemented by cutting two symmetrical narrow slits from the ground plane. The antenna is fabricated on a substrate with a dielectric constant of 4.4 and has a compact size of $18 \times 26 \times 1.6 \text{ mm}^3$. Experimental and simulation results of the fabricated antenna are found to be in good agreement. The antenna achieves an average gain of 3 dBi and efficiency of more than 80% over the operational band. Time domain analysis, which includes the group delay response and fidelity calculation, implies that minimal distortion is introduced by the proposed antenna which makes it suitable for portable pulsed UWB systems.

1. INTRODUCTION

A shared unlicensed band between 3.1–10.6 GHz is allocated to ultra-wideband (UWB) systems. In other words, the bandwidth used by these systems is 7.5 GHz which is the largest bandwidth allocated for any commercial use thus far. With such a bandwidth, the potential targets for UWB systems have high data rates and accurate positioning capabilities [1–3]. In [1], four planar UWB antennas with cuts at the edges and parasitic loops are employed. Antenna compactness is achieved in [2] by means of a meander line for current path enlargement. Also two parameterized slits provide additional degrees of freedom that help to ensure good impedance matching. In [3], a multiobjective topology is used for the optimization of the UWB antenna.

The allocated band for UWB systems is shared with existing narrowband systems. The interference caused by the radiation of UWB antennas with these systems can be eliminated by using a notch filter tuned to the required frequency band. However, adding filters would increase the complexity. An alternative method is the use of band-notched antennas where a number of frequency bands are attenuated out of the UWB spectrum.

A UWB antenna with band-notch characteristics is mostly constructed by combining a regular UWB antenna with a band-stop resonant structure. In other words, the design of band-notched UWB antennas is a two-step procedure. In the first step, a UWB is designed with good matching performance. The second step involves adding a band-stop resonator and optimizing the performance. To create the notch characteristics, two factors regarding the resonant structure to be used are considered, which are the type and location. The usually used resonator types are slot [4–6], microstrip [7, 8], coplanar waveguide (CPW) [9], and metamaterial [10–12] resonators. These resonant structures can be located either on the radiating structure or on the feeding structure. For example, slots implementing the notched-band characteristics can be placed on the radiator in a location that is either near the edges or near the feeder. The slots can take different shapes such as V shape [4], C shape [5] and U shape [6]. The notch center frequency and bandwidth are mostly determined by the dimensions of the slot (or the

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cut). The slots can also be cut on the ground plane. Normally the electrical length of the ground slot is a quarter wavelength at the notch frequency [13]. In order to obtain a high quality factor at resonance to create the notch, slots and cuts must be near the small areas joining the radiator, feed line and ground plane, or close to the feed line. Using parasitic strips is another method to achieve notched bands. These strips can be placed on the radiating aperture of the UWB antenna, and usually their effective length is a half-wavelength at the notch frequency [14]. However, a disadvantage of this method is that it has low quality factor [15]. Band-notched characteristics for planar monopole antennas can be created by using various types of microstrip resonators [7, 8] such as: open/short-circuited resonators, closed-loop resonators, and open-loop resonators. Compact CPW resonant cells (CCRC) can also be used to implement the band-notched characteristics [9]. Microstrip or CPW resonators used in UWB antennas are mostly compact because antenna miniaturization is increasingly becoming an important design requirement. Metamaterial resonators such as the split-ring resonator (SRR) and the complementary split-ring resonator (CSRR) can be utilized in UWB antennas to achieve band-notched characteristics. These resonators have small sizes and a very high quality factor [10]. Due to their small sizes, multiple SRRs and CSRRs can be used in UWB antennas to generate notches at multiple bands [11, 12].

Consumer products that require UWB antennas are usually designed to be small in size. This fact implies that UWB antennas used in such products must be compact. For planar band-notched UWB antennas, miniaturization can be achieved in two steps. The first step is to employ the techniques used in miniaturizing the UWB antenna itself. The second step is to miniaturize the resonators used to achieve the band-notched characteristics. It should be mentioned that since UWB is a pulse based communication, both frequency and time domain measurements are necessary to demonstrate that an antenna exhibits good UWB performance [15, 16].

In this paper, a compact band-notched staircase UWB antenna is developed. The evolution of the antenna from a finite ground coplanar waveguide (FG-CPW) fed strip monopole is presented in detail. The reflection coefficient, surface current and the radiation patterns of the antenna are simulated and analyzed. The antenna is fabricated, and measurements have been conducted to verify that the performance of the fabricated antenna agrees well with the simulated results. Transient analysis of the antenna is conducted to understand and estimate the pulse handling capability of the antenna.

2. ANTENNA DESIGN

The staircase-shaped band-notched UWB antenna is shown in Fig. 1. It is fed using a FG-CPW, and both the radiator and the ground are staircase-shaped. On the ground plane, two thin narrow slits are inserted. To get a better insight into the behaviour of the proposed antenna, its geometrical evolution from a FG-CPW-fed strip monopole antenna as shown in Fig. 2 is studied. The FG-CPW-fed strip monopole antenna (Antenna 1) is shown in Fig. 2(a). Top loading Antenna 1 with a rectangle patch with length (L_1) and width (W_1) results in the antenna shown in Fig. 2(b) (Antenna 2). UWB antenna is obtained by making steps both on the ground plane and the radiating element resulting in Fig. 2(c) (Antenna 3). Finally inserting thin narrow slits on the ground plane results in the band notched UWB antenna (Antenna 4) and is given in Fig. 2(d). The four antennas are simulated using Advanced Design System (ADS) where a FR4 epoxy substrate with relative permittivity $\epsilon_r = 4.4$, loss tangent $\tan \delta = 0.02$ and thickness $h = 1.6$ mm is used. The simulated reflection coefficients of the four antennas are shown in Fig. 3. Parameters of the antenna are given by $W_1 = 18$ mm, $W_2 = 15$ mm, $W_3 = 12$ mm, $W_4 = 4.15$ mm, $W_5 = 5.65$ mm, $W_6 = 7.15$ mm, $H_1 = 8$ mm, $H_2 = 2$ mm, $H_3 = 2$ mm, $d = 2$ mm, $\epsilon_r = 4.4$, and $h = 1.6$ mm. In the next sections each antenna is analyzed in detail.

2.1. Strip Monopole Antenna (Antenna 1)

The geometry of the basic FG-CPW-fed strip monopole antenna is shown in Fig. 2(a). By optimizing the parameters of this monopole, various modes can be simultaneously excited and multi-mode operation can be achieved. This fact can be utilized to develop the strip monopole into an UWB antenna. In order to have a 50Ω input impedance, the gap (G) and the strip width (W) for all antennas are calculated and are found to be $G = 0.35$ mm and $W = 3$ mm as instructed in [13], respectively. Also, the substrate used has an overall length of 30 mm and substrate width of 30 mm. A finite ground plane of length

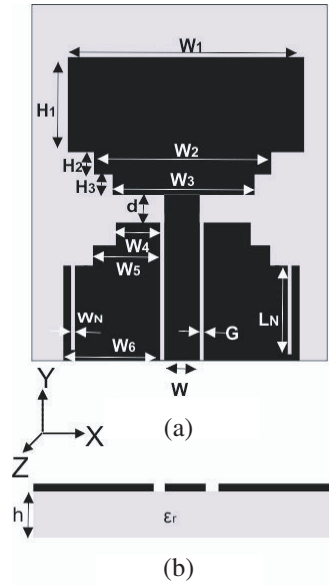


Figure 1. Geometry of the proposed band-notched staircase-shaped UWB antenna. (a) Top view. (b) Side view.

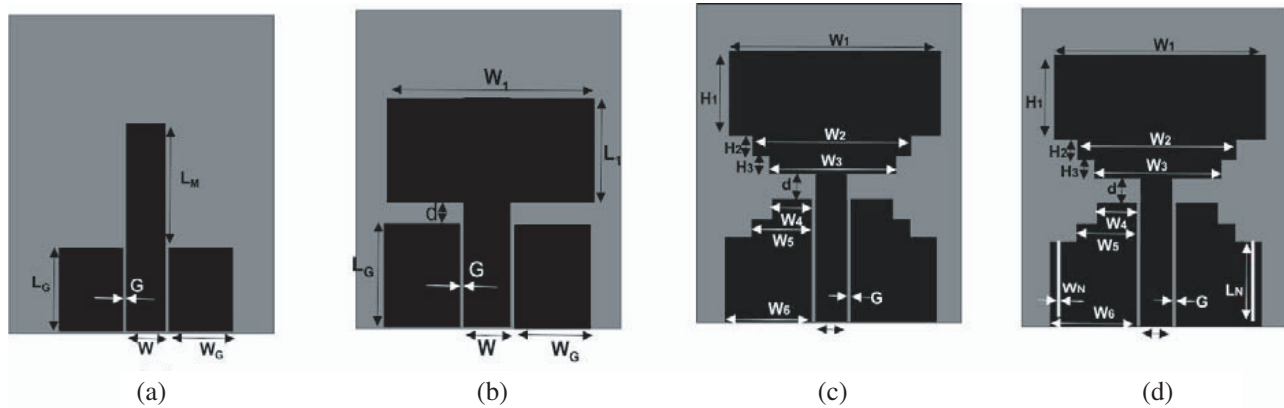


Figure 2. Evolution of the band-notched staircase-shaped UWB monopole antenna. (a) FG-CPW-fed strip monopole antenna. (b) Top loaded monopole antenna. (c) Staircase-shaped UWB monopole antenna. (d) Band-notched staircase-shaped UWB antenna.

$(L_G) = 12$ mm and width $(W_G) = 7.15$ mm is found to provide good matching performance. The strip monopole of length $(L_M) = 12$ mm is formed by extending the center conductor of the FG-CPW. From the dashed curve of Fig. 3, two resonances centered at 4 GHz and 10.3 GHz, respectively, are observed for antenna 1. However, the bandwidth of the strip monopole antenna is narrow and does not represent an UWB performance.

2.2. Top Loaded Strip Monopole Antenna (Antenna II)

Technique of top loading can be effectively applied to the strip monopole to increase the bandwidth in the low frequency range. The geometry of the top loaded monopole antenna is shown in Fig. 2(b). A rectangle of length $(L_1) = 12$ mm and width $(W_1) = 18$ mm is top loaded on the monopole at a distance $(d) = 2$ mm from the ground plane. The dotted plot in Fig. 3 shows the antenna reflection coefficient which indicates that the antenna bandwidth around the 4 GHz resonance is increased compared to that of antenna 1.

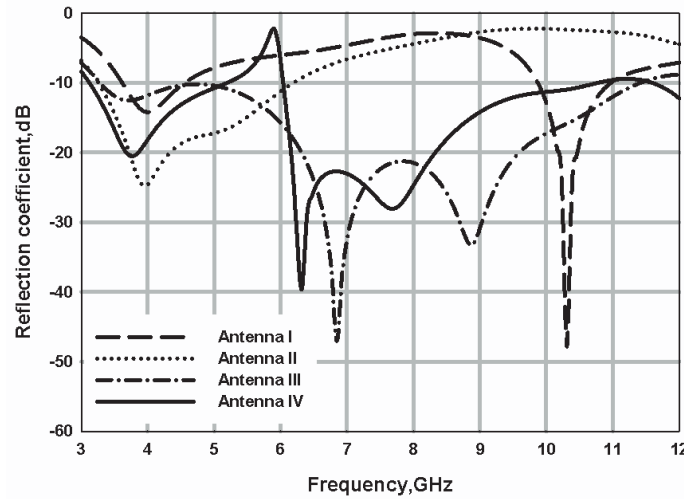


Figure 3. Simulated reflection coefficients of the four antennas of Fig. 2.

2.3. Staircase-Shaped UWB Monopole Antenna (Antenna III)

With an aim of increasing the bandwidth, steps are made on the patch and the ground plane as presented in Fig. 4, the corresponding reflection coefficients are shown in Fig. 5. It is found that for a single pair of steps as in Fig. 4(a), the -10 dB bandwidth extends from 3.1 GHz to 7.8 GHz. In the case of antenna with two pairs of steps on the loaded patch as in Fig. 4(b), the -10 dB bandwidth is from 3.1 GHz to 8.2 GHz. Finally, in addition to the two pairs of steps on the radiating patch, a pair of steps is inserted on the ground plane which can be seen in Fig. 4(c). The frequency response of this antenna shows that the -10 dB bandwidth extends from 3.1 GHz to 9.4 GHz.

To obtain a UWB response, the antenna in Fig. 4(c) is modified by inserting one more pair of steps on the ground plane forming the staircase-shaped monopole antenna (antenna III) presented in Fig. 2(c). From the dot-dash curve in Fig. 3, it can be observed that the return loss covers the range from 3.2 to 11.5 GHz. The ground plane of the antenna plays an important role in matching the antenna impedance. Modifying the partial ground plane to staircase ground plane has improved the reflection coefficient bandwidth, especially at higher frequencies. Dimensions of the antenna are $W_1 = 18$ mm, $W_2 = 15$ mm, $W_3 = 12$ mm, $W_4 = 4.15$ mm, $W_5 = 5.65$ mm, $W_6 = 7.15$ mm, $H_1 = 8$ mm, $H_2 = 2$ mm, $H_3 = 2$ mm, and $d = 2$ mm.

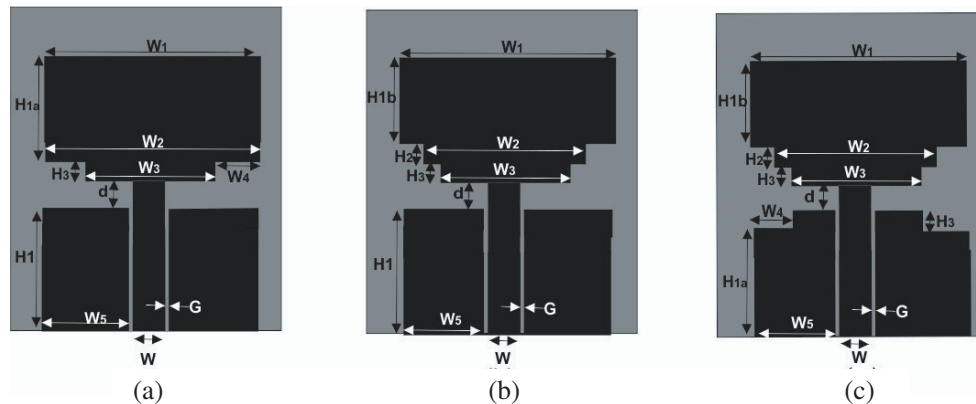


Figure 4. Geometries of the top loaded monopole antenna with (a) A pair of steps on the patch. (b) Two pairs of steps on the patch. (c) Two pairs of steps on the patch and one on the ground.

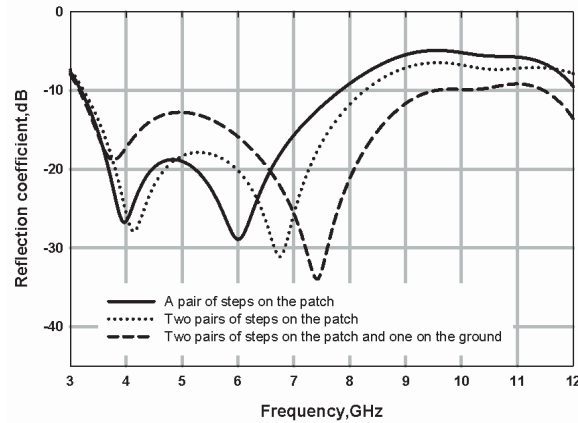


Figure 5. The reflection coefficients of the antennas in Fig. 4.

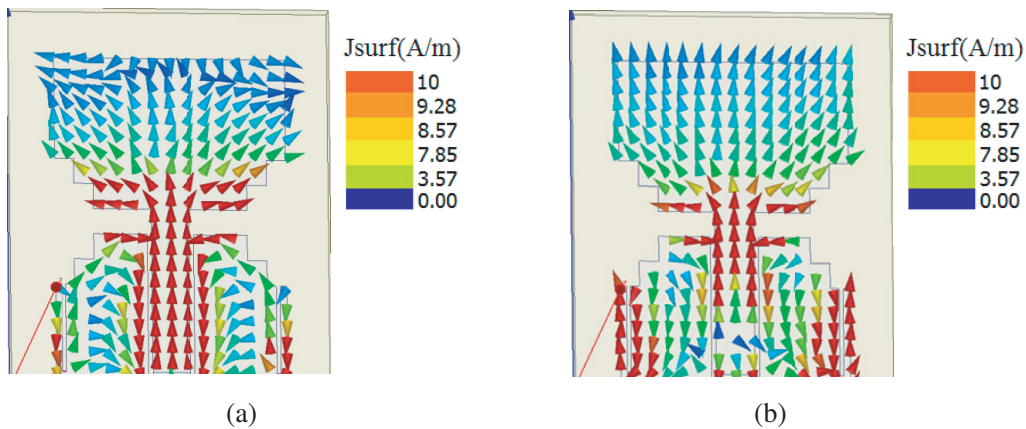


Figure 6. Surface current density distributions of the band-notched staircase-shaped UWB monopole antenna at (a) 3.8 GHz (passband). (b) 5.8 GHz (notch band).

2.4. Band-Notched Staircase-Shaped UWB Antenna (Antenna IV)

The UWB antenna (antenna III) presented in the preceding section is modified by adding a stopband resonant structure to the ground plane to achieve band-notched characteristics. This is done by inserting two symmetrical slits of length L_N and width W_N on the ground plane. The two slits are designed to notch out WLAN frequencies (5.15 GHz–5.85 GHz). The dimensions of the slits was found to be $L_N = 7$ mm, and $W_N = 0.3$ mm. Reflection coefficient of the band-notched UWB monopole antenna is illustrated in Fig. 3 (solid curve). The -10 dB bandwidth of the antenna extends from 3.1 GHz to 10.7 GHz. In addition, a notch band from 5.1 GHz to 6 GHz is obtained, so that the WLAN frequency band is completely notched out.

Surface current density distributions of the antenna in the notched band and the passband are illustrated in Fig. 6. In the notch frequency (5.8 GHz), current mainly flows around the slits, whereas the current in the other parts of the structure is minimal. In the passband such as at 3.8 GHz, strong current is available in the antenna, and it will radiate.

3. RESULTS

A prototype of the proposed antenna presented in Section 2.4 is fabricated, and its photograph is shown in Fig. 7. In this section, the results of measuring conventional antenna characteristics such as

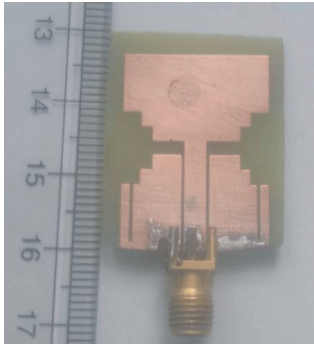


Figure 7. Photograph of the band-notched staircase-shaped UWB antenna.

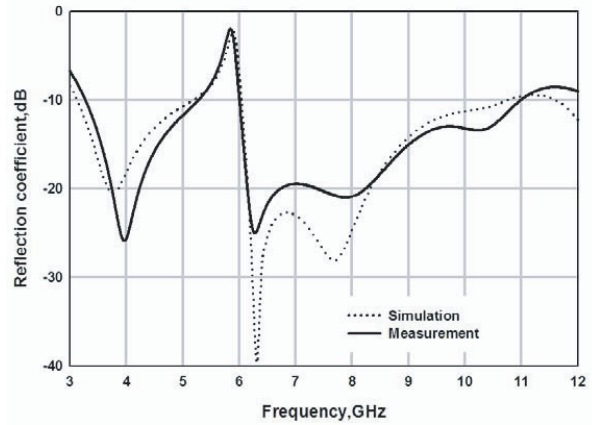


Figure 8. Measured and simulated reflection coefficients of the antenna.

the reflection coefficient, radiation patterns, gain and efficiency are reported. Also, the time domain performance of the antenna is investigated.

3.1. Antenna Characteristics

Figure 8 gives a comparison between measured and simulated reflection coefficients of the band-notched staircase-shaped UWB monopole antenna. A -10 dB bandwidth from 3.25 GHz to 11.0 GHz with resonances at 4.0 GHz, 6.2 GHz, and 7.9 GHz is measured. In addition a notch band from 5.15–6.0 GHz is also obtained. Simulated bandwidth extends from 3.1 GHz to 11 GHz. The measured and simulated results are in good agreement. Fig. 9 shows the radiation pattern measurements of the proposed antenna in the E and H planes. The cross polarization for the three resonances are plotted in the same figure. It is noticed from the plots that omnidirectional like pattern is obtained for each resonance. Also, good measured cross polar isolation levels were observed. The gain of the band-notched staircase-shaped antenna is shown in Fig. 10(a). An average gain of 3 dBi is noted over the entire operating band. A reduction in gain greater than 5 dBi is obtained for the band-notched staircase-shaped UWB antenna. The antenna radiation efficiency measurement is shown in Fig. 10(b). Radiation efficiency of the antenna is measured using Wheeler Cap method [17]. Radiation efficiency greater than 80% is obtained in the passband, whereas the radiation efficiency at the rejected band is low.

3.2. Time Domain Performance of the Antenna

In this section, a discussion of the time domain characteristics of the proposed band-notched staircase-shaped UWB antenna is presented. Ideally, the received UWB signal should maintain exactly the same shape as the source pulse. However, the received signal may be distorted compared to the transmitted signal. Therefore, the time domain measurements of UWB antenna are indispensable, and the antenna time domain performance should be carefully studied to make sure that the unwanted distortion is minimized.

A typical transmitting/receiving antenna system is set up for that purpose using the proposed antenna. Then, the transmission coefficient S_{21} is measured by aligning the two identical antennas along the face-to-face and side-by-side orientations. The distance between the antennas are set to be 60 cm to satisfy the far field criteria. Subsequently, the transfer function $H(\omega)$ is calculated from the measured S_{21} for each orientation as in [18].

The fourth order Rayleigh pulse is the waveform template chosen for pulse characterization and analysis of the proposed antenna because its spectrum directly matches the UWB band. To qualitatively evaluate the distortion performance, the received pulses at the two orientations (face to face and side by side) need to be calculated. This is done in two steps for each orientation. First, the Inverse Fast

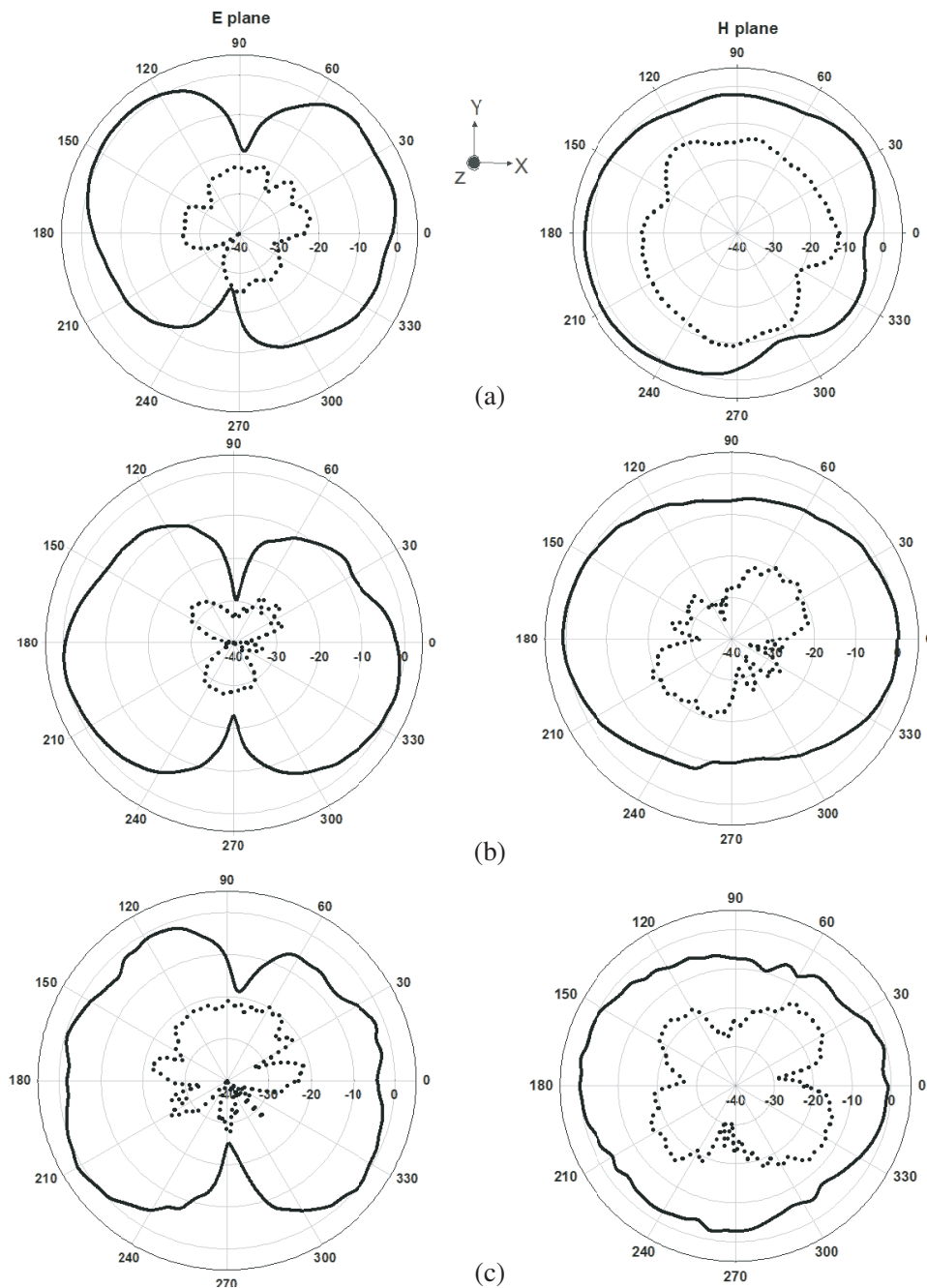


Figure 9. Measured principal plane radiation patterns of the band notched UWB antenna at (a) 4.0 GHz. (b) 6.2 GHz. (c) 7.9 GHz.

Fourier Transform (IFFT) is applied. The result is then convolved with the source pulse to obtain the received UWB pulse. HP 8510C network analyzer is used in the measurements and MATLAB is used for plotting the results. In Fig. 11(a), the waveforms of the transmitted and received pulses are shown. By comparing the transmitted and received pulses, it can be observed that the received pulses maintain the shape of the transmitted pulse to a great extent. As a result, it can be concluded that the distortion caused by the antenna to the transmitted pulse is feeble.

A figure of merit to quantitatively evaluate the distortion introduced by an UWB receiving antenna is the fidelity factor (FF). Basically, it is the cross correlation between the input and the received pulses.

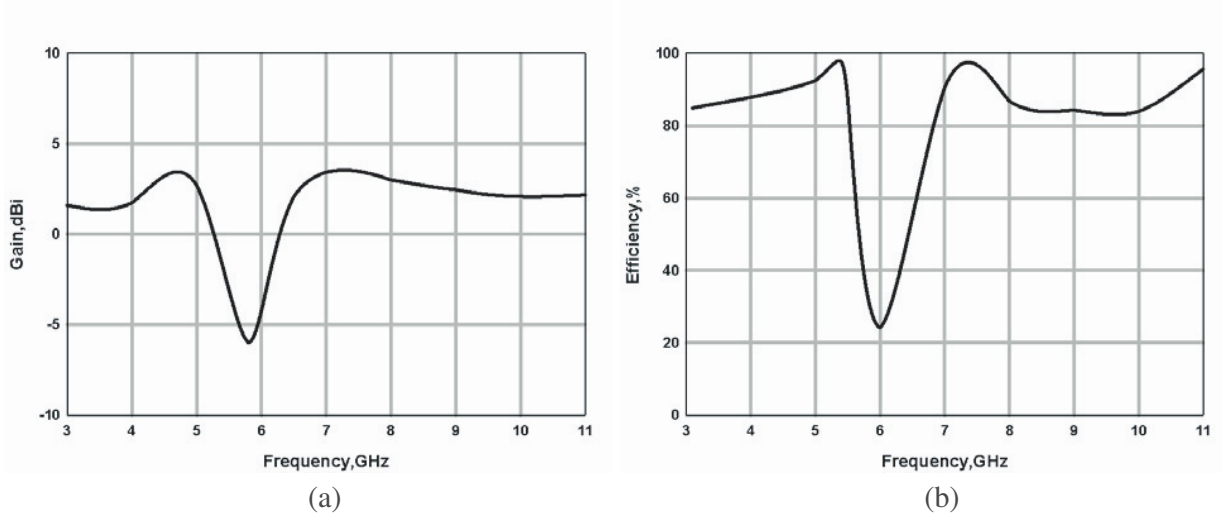


Figure 10. Measured characteristics of the proposed antenna. (a) Gain. (b) Radiation efficiency.

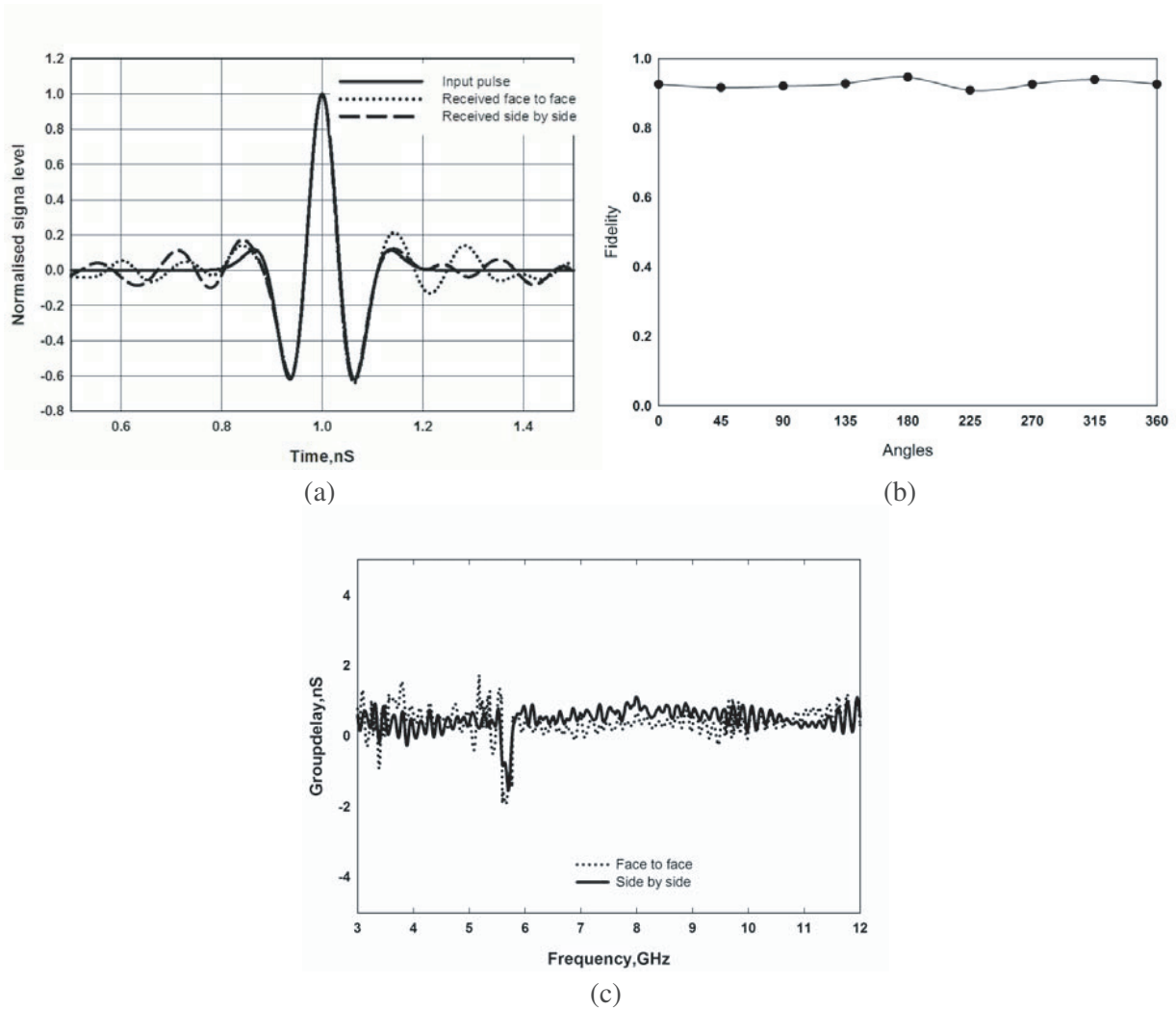


Figure 11. Time domain performance of the proposed antenna. (a) Input and received pulses. (b) Fidelity factor. (c) Measured group delay.

When the value of FF is unity, the input and received pulses are identical, and no distortion occurs. The FF is a function of the orientation of the received antenna. Fidelity factor F is defined by

$$F = \max_{\tau} \frac{\int x(t) \cdot \int y(t - \tau) dt}{\sqrt{\int |x(t)|^2 \cdot dt \int |y(t)|^2 dt}} \quad (1)$$

where τ is the time delay which is varied to maximize the numerator. The Fidelity factor is deduced from the measured and simulated data for different receiving antenna orientations, with $x(t)$ as the incident and $y(t)$ as the received waveform [19].

In our case, the FF is measured in the H -plane between 0° and 360° , and the result is shown in Fig. 11(b). The obtained value of FF is greater than 0.9 in all measured azimuth angles, which indicate that the proposed antenna introduces minimal distortion effects to the transmitted signal. Maximum fidelity for the antenna is found to be 94.61%.

An important parameter in UWB communication is the group delay, which represents the degree of distortion of the pulse signal. The group delay is measured by placing two identical antennas in the far field. A non distorted structure is characterized by a constant group delay. Fig. 11(c) shows the group delay comparison for the two different orientations, face to face and side by side. Group delay variations are less than 1ns for both orientations except at the notch frequency. At the notch frequency, a sudden decrease in group delay is observed, which may be due to phase advancing at the notch frequency.

4. CONCLUSION

In this paper, the design of a simple compact band-notched UWB monopole antenna, which is FG-CPW-fed, is presented. Both the radiator and the ground plane of the proposed antenna are stair-shaped which makes it matched over the UWB band. Two narrow slits are cut from the ground plane to reject a specific narrow band which is designed here to be at the WLAN frequencies. The accomplished band rejection makes it unnecessary to use additional filters which are not desired in space-constrained portable wireless systems. The proposed geometry of the antenna is developed from that of a FG-CPW-fed strip monopole in several stages, and this evolution in design is analyzed in detail. Measurements show that the -10 dB bandwidth of the antenna is in the range 3.25–11.0 GHz with a notched band in the range 5.15–6.0 GHz. In the operational band, the antenna accomplishes an efficiency of more than 80% and an average gain of 3 dBi. In the notched band, however, the measured efficiency and gain suffer a substantial reduction as desired. The radiation patterns of the proposed antenna were also measured, and a monopole-like behaviour was observed along with low cross-polarization levels. The pulse handling capability of the antenna is assessed by performing time-domain analysis, and minimal distortion is observed.

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